

Failed gamma-ray bursts and orphan afterglows

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ABSTRACT

It is believed that orphan afterglow searches can help to measure the beaming angle in gamma-ray bursts (GRBs). Great expectations have been put on this method. We point out that the method is in fact not as simple as we originally expected. Due to the baryon-rich environment that is common to almost all popular progenitor models, there should be many failed gamma-ray bursts, i.e., fireballs with Lorentz factor much less than 100 — 1000, but still much larger than unity. In fact, the number of failed gamma-ray bursts may even be much larger than that of successful bursts. Owing to the existence of these failed gamma-ray bursts, there should be many orphan afterglows even if GRBs are due to isotropic fireballs, then the simple discovery of orphan afterglows never means that GRBs be collimated. Unfortunately, to distinguish a failed-GRB orphan and a jetted but off-axis GRB orphan is not an easy task. The major problem is that the trigger time is unknown. Some possible solutions to the problem are suggested.

Key words: stars: neutron – ISM: jets and outflows – gamma-rays: bursts

1 INTRODUCTION

The detection of X-ray, optical and radio afterglows from some well-localized gamma-ray bursts (GRBs) definitely shows that at least most long GRBs are of cosmological origin (e.g., Costa et al. 1997; Frail et al. 1997; Galama et al. 1998; Akerlof et al. 1999; Zhu et al. 1999). The so called fireball model is thus strongly favoured. However, we are still far from resolving the puzzle of GRBs (Piran 1999; van Paradijs, Kouveliotou & Wijers 2000). A major problem is that we do not know whether GRBs are due to highly collimated jets or isotropic fireballs, so that the energetics involved cannot be determined definitely (e.g., Pugliese, Falcke & Biermann 1999; Kumar & Piran 2000; Dar & Rújula 2000; Wang & Loeb 2001; Rossi, Lazzati & Rees 2002). This issue has been extensively discussed in the literature.

Generally speaking, three methods may help to determine the degree of beaming in GRBs. First, based on analytic solutions, it has been proposed that optical afterglows from a jetted GRB should be characterized by a break in the light curve during the relativistic phase, i.e., at the time when the Lorentz factor of the blastwave is $\gamma \sim 1/\theta$, where θ is the half opening angle (Rhoads 1997; Kulkarni et al. 1999; Mészáros & Rees 1999). Some GRBs such as 990123, 990510 are regarded as good examples (Castro-Tirado et al.

1999; Wijers et al. 1999; Harrison et al. 1999; Halpern et al. 2000; Pian et al. 2001; Castro Ceron et al. 2001; Sagar et al. 2001). However, detailed numerical studies show that the break is usually quite smooth (Panaitescu & Mészáros 1998; Moderski, Sikora & Bulik 2000), and Huang et al. went further to suggest that the light curve break should in fact occur at the trans-relativistic phase (Huang et al. 2000a, b, c, d). Additionally, many other factors can also result in light curve breaks, for example, the cooling of electrons (Sari, Piran & Narayan 1998), a dense interstellar medium (Dai & Lu 1999), or a wind environment (Dai & Lu 1998a; Chevalier & Li 2000; Panaitescu & Kumar 2000). All these facts combine together to make the first method not so conclusive. Second, Gruzinov (1999) argued that optical afterglows from a jet can be strongly polarized, in principle up to tens of percents. Some positive observations have already been reported (Wijers et al. 1999; Rol et al. 2000). But polarization can be observed only under some particular conditions, i.e., the co-moving magnetic fields parallel and perpendicular to the jet should have different strengths and we should observe at the right time from the right viewing angle (Gruzinov 1999; Hjorth et al. 1999; Mitra 2000).

The third method was first proposed by Rhoads (1997), who pointed out that due to relativistic beaming effects, γ -ray radiation from the vast majority of jetted GRBs cannot be observed, but the corresponding late time afterglow emission is less beamed and can safely reach us. These afterglows are called orphan afterglows, which means they are not as-

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sociated with any detectable GRBs. The ratio of the orphan afterglow rate to the GRB rate might allow measurement of the GRB collimation angle. Great expectations have been put on this method (Rhoads 1997; Mészáros, Rees & Wijers 1999; Lamb 2000; Paczyński 2000; Djorgovski et al. 2001). In fact, the absence of large numbers of orphan afterglows in many surveys has been regarded as evidence that the collimation cannot be extreme (Rhoads 1997; Perna & Loeb 1998; Greiner et al. 1999; Grindlay 1999; Rees 1999).

Recently Dalal, Griest & Pruet (2002) argued that measurement of the GRB beaming angle using optical orphan searches is extremely difficult. The main reason is that when the afterglow emission from a jet begins to go into a much larger solid angle than the initial burst does, the optical flux density usually becomes very low. Generally speaking, this problem can be overcome by improving the detection limit. In fact, an interesting result was recently reported by Vanden Berk et al. (2002), who discovered a possible optical orphan at $z = 0.385$. They suggested that GRBs should be collimated.

In this article, we will point out another difficulty associated with the third method: there should be many “failed gamma-ray bursts (FGRBs)”, i.e., baryon-contaminated fireballs with initial Lorentz factor $\gamma_0 \ll 100$. FGRBs cannot be observed in gamma-rays, but their long-lasting afterglows are detectable, thus they will also manifest themselves as orphan afterglows. Our paper is organized as follows. In Section 2 we explain the concept of FGRBs. Section 3 describes the difficulty in distinguishing an FGRB orphan and a jetted GRB orphan. Some possible solutions that may help to overcome the difficulty are suggested. Section 4 is a brief discussion.

2 FAILED GAMMA-RAY BURSTS AND THEIR AFTERGLOWS

Occurring in the deep Universe, GRBs are the most relativistic phenomena ever known. The standard fireball model (Mészáros & Rees 1992; Dermer, Böttcher & Chiang 1999) requires that to successfully produce a GRB, the initial Lorentz factor of the blastwave should typically be $\gamma_0 \geq 100$ — 1000 during the main burst phase (Piran 1999; Lithwick & Sari 2000). Generally speaking the requirement of ultra-relativistic motion is to avoid the so called “compactness problem”. A modest variation in the Lorentz factor will result in a difference of the opacity of the high-energy γ -ray photons by a factor of $\sim 10^3$ (Totani 1999). Additionally, assuming synchrotron radiation, the observed peak frequency is strongly dependent on γ , $\nu_m \propto \gamma^4$ (Mészáros, Rees & Wijers 1998). Thus a Lorentz factor of $\gamma_0 \leq 50$ makes the blastwave very inefficient in emitting γ -ray photons.

So, to successfully produce a GRB, we need $\gamma_0 \geq 100$ — 1000. However, theoretically it is not easy to construct a model to generate such ultra-relativistic motions. Currently there are mainly two kinds of progenitor models, the collapse of massive stars (with mass $M \geq 40M_\odot$), or the collision of two compact stars (such as two neutron stars or a neutron star and a black hole). Since a baryon-rich environment is involved in all these models, some researchers are afraid that the baryon-contamination problem may exist. But this problem maybe is not as serious as we previously expected.

Let us first take the collapsar model (MacFadyen & Woosley 1999) as an example. We can imagine that the baryon mass and energy released in different collapsar events should vary greatly, then γ_0 of the resultant fireballs may also vary in a relatively wide range. In most cases, γ_0 should be very low (i.e., $\gamma_0 \ll 100$), but there still could be a few cases (e.g., one percent or even one in a thousand) in which the fireball is relatively clean so that the blastwave can be successfully accelerated to $\gamma_0 \geq 100$ — 1000 and produces a GRB. Since the collapsar rate is high enough in a typical galaxy, there should be no problem that such collapsars can meet the requirement of GRB rate (i.e., 10^{-7} — 10^{-6} event per typical galaxy per year, under isotropic assumption). Cases are similar in the collisions of two compact stars.

In short, we cannot omit an important fact: if GRBs are really due to isotropic fireballs, then there should be much more failed GRBs (i.e., fireballs with Lorentz factor much less than one hundred, but still much greater than unity). These FGRB fireballs can contain similar initial energy as normal GRB fireballs, i.e., $E_0 \sim 10^{51}$ — 10^{53} ergs, but they are polluted by baryons with mass $M_0 \sim 10^{-5}$ — $10^{-3}M_\odot$. Radiation from these FGRBs should mainly be in x-ray bands in the initial bursting phase, not in γ -ray bands. In fact, BeppoSAX team has reported the discovery of several anomalous events named as fast X-ray transients, X-ray rich GRBs, or even X-ray-GRBs. They resemble usual GRBs except that they are extremely X-ray rich (Frontera et al. 2000; Kippen et al. 2001; Gandolfi & Piro 2001). Observational data on this kind of events are being accumulated rapidly. Recent good examples include GRBs 011030, 011130 and 011211 (Gandolfi et al. 2001a, b; Ricker et al. 2001). We propose that these events are probably just FGRBs.

Huang et al. (1998) and Dai, Huang & Lu (1999) have pointed out that for afterglow behaviour, the parameter E_0 is decisive, while M_0 is only of minor importance, especially at late stages. So, FGRBs should also be associated with prominent afterglows. In Figure 1 we compare the theoretical optical afterglows from FGRBs with those from isotropic GRBs and jetted GRBs. We can see that the light curve of an FGRB afterglow differs from that of a successful isotropic burst only slightly, i.e., only notable at early stages. In our calculations, we have used the methods developed by Huang et al. (1999a, b, 2000b, d), i.e., for the dynamical evolution of isotropic fireballs we use

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_0 + \epsilon m + 2(1 - \epsilon)\gamma m}, \quad (1)$$

where m is the swept-up mass and ϵ is the radiation efficiency. Eq. (1) has been proved to be proper in both ultra-relativistic phase and non-relativistic phase (Huang, Dai & Lu 1999a, b). For jetted ejecta, the following equation is added (Huang et al. 2000b, d),

$$\frac{d\theta}{dt} = \frac{c_s(\gamma + \sqrt{\gamma^2 - 1})}{R}, \quad (2)$$

where R is the blastwave radius, and the co-moving sound speed c_s is given realistically by

$$c_s^2 = \hat{\gamma}(\hat{\gamma} - 1)(\gamma - 1) \frac{1}{1 + \hat{\gamma}(\gamma - 1)} c^2, \quad (3)$$

with $\hat{\gamma} = (4\gamma + 1)/(3\gamma)$ the adiabatic index.

In fact, in beamed GRB models, there should also be

many FGRBs, i.e., beamed ejecta with $1 \ll \gamma_0 \ll 100$. We call them beamed FGRBs. Afterglow from beamed FGRBs has also been illustrated in Figure 1. In this article emphasises will be put on isotropic FGRBs, so by using “FGRBs” we will only mean isotropic FGRBs unless stated explicitly.

3 ORPHAN AFTERGLOWS

Both FGRBs and jetted but off-axis GRBs can produce isolated fading objects, i.e., orphan afterglows. Theoretically, when orphan afterglows are really discovered observationally, it is still risky to conclude that GRBs are beamed. We should study these orphans carefully to determine whether they come from FGRBs or Jetted GRBs. However, we will show below that it is not an easy task.

3.1 Difficulty in using orphan afterglows

Usually the light curve of GRB afterglows is plotted as $\log S_\nu$ vs. $\log t$, where S_ν is the flux density at observing frequency ν and t is observer’s time measured from the burst trigger. In such plots, the behaviour of afterglows from isotropic GRBs and jetted ones are possibly quite different. The former is generally characterized by a simple flat straight line with slope $\sim -1.0 - -1.3$ and the latter can be characterized by a break in the light curve or by a steep straight line with a slope sharper than ~ -2.0 (Figure 1, also see Huang et al. 2000a, b, c, d). But for orphan afterglow observations, the derivation of such a $\log S_\nu - \log t$ light curve is not direct: we do not know the trigger time so that the exact value of t for each observed data point cannot be determined.

As the first step, the best that we can do is to produce a light curve with a linear time axis, which, however, is of little help for unveiling the nature of the orphan. Figure 2 illustrates the matter. In this figure we plot $\log S_\nu$ vs. t for the two kinds of orphans theoretically. The uncertainty in trigger time means the observed light curve can be shifted along X axis, while the unknown distance results in a shift along Y axis. We see that after some simple manipulations, the segment AB on the dashed curve (i.e., from $t = 18$ d to $t = 55$ d) can be shifted to a place (A'B') that differs from the solid line only slightly. It hints that a linear light curve as long as ~ 37 days is still not enough. Note that the solid and the dashed curves in Figure 2 are only two examples. The variation of some intrinsic parameters, such as E_0 , n , γ_0 , ξ_e , ξ_B^2 , p , θ_0 and θ_{obs} as defined in the caption of Figure 1, can change the shape of the two curves notably, thus brings in much more difficulties.

In Figure 3, we compare the theoretical $\log S_\nu - \log t$ light curves of optical afterglows from FGRBs and jetted but off-axis GRBs directly. To investigate the influence of the uncertainty in trigger time, we also shift the light curve of FGRBs by $t \pm 3$ d, $t \pm 10$ d and $t \pm 30$ d intentionally. From the dashed curves, we can see that the shape of the FGRB afterglow light curve is seriously affected by the uncertainty of the trigger time. But fortunately, these dashed curves still differ from the theoretical light curve of the jetted GRB orphan markedly, i.e., they are much flatter at very late stages. This means it is still possible for us to discriminate them. In Figure 4, similar results to Figure 3 are given, but this time the light curve of the jetted GRB orphan is shifted. Again

we see that the two kinds of orphans can be discriminated by their late time behaviour.

Figures 3 and 4 explain what we should do when an orphan afterglow is discovered. First, we have to assume a trigger time for it arbitrarily, so that the logarithmic light curve can be plotted. We then need to change the trigger time to many other values to see how the light curve is affected. In all our plots, we should pay special attention to the late time behaviour, which will be less affected by the uncertainty in the trigger time. If the slope tends to be $\sim -1.0 - -1.3$, then the orphan afterglow may come from an FGRB event. But if the slope tends to be steeper than ~ -2.0 , then it is very likely from a jetted but off-axis GRB.

In fact, from Figure 1, we know that for all kinds of GRBs, either successful or failed, the optical afterglow approximately follows a simple power-law decay at late stages (i.e., $S_R \approx kt^{-\alpha}$) so that the light curve is a straight line. In such a relation, if we shift the time by T ,

$$S_R \approx k(t + T)^{-\alpha}, \quad (4)$$

then the line would become curved. The slope at each point on the curve is

$$\frac{d \log S_R}{d \log t} = -\alpha \left(\frac{t}{t + T} \right). \quad (5)$$

For positive T values the lines bend up-ward, while for negative values the lines bend down-ward. It hints that in plotting the orphan afterglow light curve, we could select the trigger time properly to get a straight line at late stages, then we can determine not only the late time slope, but also the true trigger time. In other words, we can use

$$\frac{d^2 \log S_R}{d(\log t)^2} \equiv 0 \quad (6)$$

as the condition to determine the trigger time and to get the straight line at late stages.

However, we must bear in mind that it is in fact not an easy task. First, to take the process we need to follow the orphan as long as possible, and the simple discovery of an orphan is obviously insufficient. Note that currently optical afterglows from most well-localized GRBs can be observed for only less than 100 days. It is quite unlikely that we can follow an orphan for a period longer than that. Second, since the orphan is usually very faint, errors in the measured magnitudes will seriously prevent us from deriving the straight line. Due to all these difficulties, a satisfactory light curve is usually hard to get for most orphans.

We see that measurement of the GRB beaming angle using orphan searches is not as simple as we originally expected. In fact, it is impractical to some extent. Recently it was suggested by Rhoads (2001) that GRB afterglows can be effectively identified by snapshot observations made with three or more optical filters. The method has been successfully applied to GRB 001011 by Gorosabel et al. (2001). It is believed that this method is also helpful for orphan afterglow searches. However, please note that a jetted GRB orphan and an FGRB one still cannot be discriminated directly.

3.2 Possible solutions

We have shown that the derivation of a satisfactory light curve for an orphan afterglow is difficult. The major problem

is that we do not know the trigger time. Anyway, there are still some possible solutions that may help to determine the onset of an orphan afterglow.

Firstly, of course we should improve our detection limit so that the orphan afterglow could be followed as long as possible. The longer we observe, the more likely that we can get the true late-time light curve slope. Secondly, we know that FGRBs usually manifest themselves as fast X-ray transients or X-ray-GRBs. If an orphan can be identified to associate with such a transient, then it is most likely an FGRB one. In this case, the trigger time can be well determined.

Thirdly, maybe in some rare cases we are so lucky that the rising phase of the orphan could be observed. For a jetted GRB orphan the maximum optical flux is usually reached within one or two days and for an FGRB orphan it is even within hours. Then the uncertainty in trigger time is greatly reduced. Additionally, a jetted GRB orphan differs markedly from an FGRB one during the rising phase. The former can be brightened by more than one magnitude in several hours (see Figures 1 — 4), while the brightening of the latter can hardly be observed. So, if an orphan afterglow with a short period of brightening is observed, then it is most likely a jetted GRB orphan. Of course, we should first be certain that it is not a supernova.

Fourthly, valuable clues may come from radio observations. In radio bands, the light curve should be highly variable at early stages due to interstellar medium scintillation, and it will become much smoother at late times. So the variability in radio light curves provides useful information on the trigger time. And fifthly, in the future maybe gravitational wave radiation or neutrino radiation associated with GRBs could be detected due to progresses in technology, then the trigger time of an orphan could be determined directly and accurately. In fact, with the successful detection of gravitational waves or neutrino emission, our understanding on GRB progenitors will surely be promoted greatly (Paolis et al. 2001).

Sixthly, the redshift of the orphan afterglow can help us greatly in determining the isotropic energy involved, which itself is helpful for inferring the trigger time. Seventhly, the microlensing effect may be of some help. Since the size of the radiation zone of a jetted GRB orphan is much smaller than that of an FGRB one, they should behave differently when microlensed.

Finally, although a successful detection of some orphan afterglows does not directly mean that GRBs be collimated, the negative detection of any orphans can always place both a stringent lower limit on the beaming angle for GRBs and a reasonable upper limit for the rate of FGRBs.

4 CONCLUSION AND DISCUSSION

To successfully produce a GRB, the blastwave should be ultra-relativistic, with Lorentz factor typically larger than 100 — 1000. However, in almost all popular progenitor models, the environment is unavoidably baryon-rich. We believe that only in very rare cases can an ultra-relativistic blastwave successfully break out to give birth to a GRB, and there should be much more failed GRBs, i.e., fireballs with Lorentz factor much less than 100 but still much larger than

unity. In fact, this possibility has also been mentioned by a number of authors, such as Mészáros & Waxman (2001).

Owing to the existence of FGRBs, there should be many orphan afterglows even if GRBs are due to isotropic fireballs. Then the simple discovery of orphan afterglows does not necessarily mean that GRBs be highly collimated. To make use of information from orphan afterglow surveys correctly, we should first know how to discriminate a jetted GRB orphan and an FGRB one. This can be done only by checking the detailed afterglow light curve. However, we have shown that the derivation of a satisfactory light curve for an orphan afterglow is difficult. The major problem is that we do not know the trigger time.

In Section 3.2, some possible solutions to the problem are suggested. Unfortunately many of these solutions are still quite impractical in the foreseeable future, which means measure of GRB beaming angle using orphan afterglow searches is extremely difficult currently. However, special attention should be paid to the second solution. Usually, FGRBs manifested themselves as fast X-ray transients during the main burst phase, while jetted but off-axis GRBs went unattended completely. If the fast X-ray transients (or X-ray-GRBs) observed by BeppoSAX are really due to FGRBs, then afterglows should be detectable. We propose that this kind of events should be followed rapidly and extensively in all bands, just like what we are doing for GRBs. If observed, afterglows from these anomalous events can be used to check our concept of FGRBs, and even to test the fireball model under quite different conditions (i.e., when $\gamma_0 \ll 100$). Also, these FGRBs can provide valuable information for our understanding of GRBs, especially on the progenitor models. Note that beamed FGRBs can also give birth to fast X-ray transients if they are directed toward us, but afterglows from such a beamed FGRB and an isotropic FGRB can be discriminated easily from the light curves (see Figure 1).

It is very interesting to note that optical afterglows from two X-ray-GRBs, 011130 and 011211, have been observed (Garnavich, Jha & Kirshner 2001; Grav et al. 2001). Their redshifts were measured to be $z = 0.5$ and 2.14 respectively (Jha et al. 2001; Fruchter et al. 2001), eliminates the possibility that they were ordinary classic GRBs residing at extremely high redshifts ($z \geq 10$). We propose that they should be FGRBs (either isotropic or beamed) or just jetted GRB “orphan”. However, the observational data currently available are still quite poor so that we could not determine their nature definitely. As for other X-ray-GRBs without a measured redshift, the possibility that they were at redshifts of $z \geq 10$ can not be excluded.

Finally, the concept of FGRBs is based on the fact that most popular progenitor models for GRBs are baryon-rich. But cases are quite different for another kind of progenitor models where strange stars are involved. Strange stars, composed mainly of u, d, and s quarks, are compact objects which are quite similar to neutron stars observationally (Alcock, Farhi & Olinto 1986). A typical strange star (with mass $\sim 1.4M_\odot$) can have a normal matter crust of less than $\sim 2 \times 10^{-5}M_\odot$ (Alcock, Farhi & Olinto 1986), or even as small as $\sim 3 \times 10^{-6}M_\odot$ (Huang & Lu 1997a, b). Then baryon contamination can be directly avoided if GRBs are due to the phase transition of neutron stars to strange stars (Cheng & Dai 1996; Dai & Lu 1998b) or collisions of bi-

nary strange stars. In these models, there should be very few FGRBs.

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Note added after acceptance (**this paragraph might not appear in the published version**): The optical orphan at $z=0.385$ reported by Vanden Berk et al. (2002) has recently been proved to be an unusual radio-loud AGN (Galiam et al. 2002, astro-ph/0202354), and X-ray GRB 011211 was found to be in fact an ordinary classic GRB (Frontera et al., GCN 1215). Additionally, the optical identification of X-ray GRB 011130 might also be incorrect (Frail et al., GCN 1207). We sincerely thank Nicola Masetti for private communication.

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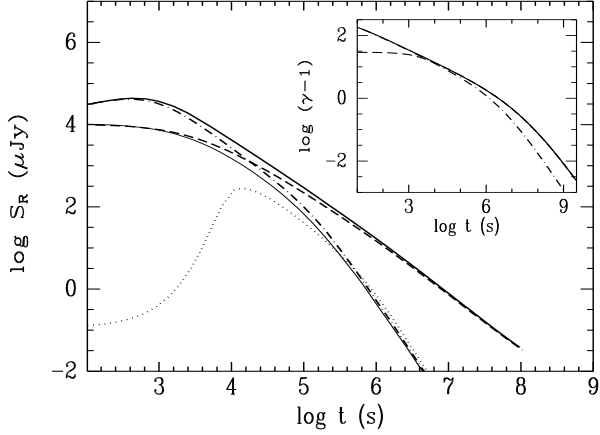


Figure 1. Theoretical R band light curves of GRB afterglows. In our calculations we have taken the following common parameters: the isotropic energy $E_0 = 10^{53}$ ergs, the interstellar medium density $n = 1 \text{ cm}^{-3}$, electron energy fraction $\xi_e = 0.1$, magnetical energy fraction $\xi_B^2 = 10^{-4}$, electron power-law energy index $p = 2.5$, and the luminosity distance $d = 1 \text{ Gpc}$. For jets, we take the initial half opening angle $\theta_0 = 0.1$. The thick solid line is plotted for a usual isotropic GRB with $\gamma_0 = 300$. The dashed line represents an isotropic FGRB orphan with $\gamma_0 = 30$. The dash-dotted line corresponds to an on-axis jetted GRB with $\gamma_0 = 300$, and the dotted line is for a jetted but off-axis GRB orphan with viewing angle $\theta_{\text{obs}} = 0.15$. The thin solid line is for a beamed FGRB with $\gamma_0 = 30, \theta_{\text{obs}} = 0$. Inset shows the evolution of the Lorentz factor correspondingly. Note that $\gamma(t)$ of the beamed FGRB is not shown, since it is too close to the dashed curve at early times and too close to the dash-dotted line at late stages.

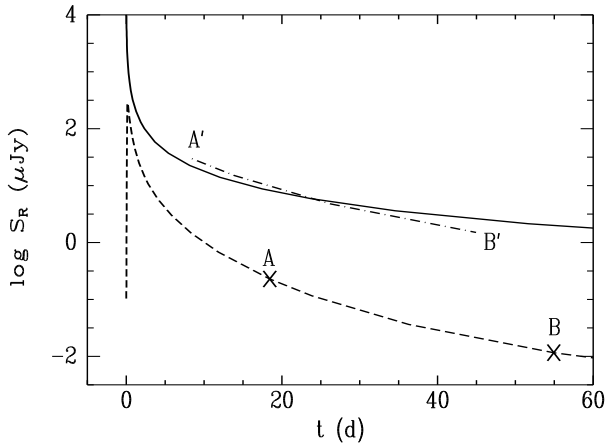


Figure 2. Sample light curves of the two kinds of orphan afterglows plotted with a linear time axis. The solid line represents an isotropic FGRB and the dashed line represents a jetted but off-axis GRB orphan. Parameters are the same as in Fig. 1. Points A and B on the dashed curve are at $t = 18 \text{ d}$ and $t = 55 \text{ d}$ respectively. The dash-dotted line (A'B') is plotted by shifting curve AB with $t - 10 \text{ d}$ and $S_R \times 130$. Note that A'B' deviates from the solid line only marginally.

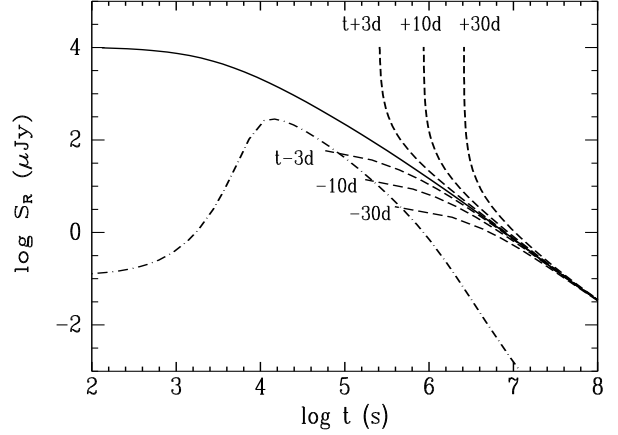


Figure 3. Direct comparison of the two kinds of orphan afterglows. The solid line represents the optical light curve of an isotropic FGRB and the dash-dotted line corresponds to a jetted but off-axis GRB orphan. The dashed lines are drawn by shifting the solid line by $t \pm 3 \text{ d}$, $t \pm 10 \text{ d}$, and $t \pm 30 \text{ d}$ respectively. Parameters are the same as in Fig. 1.

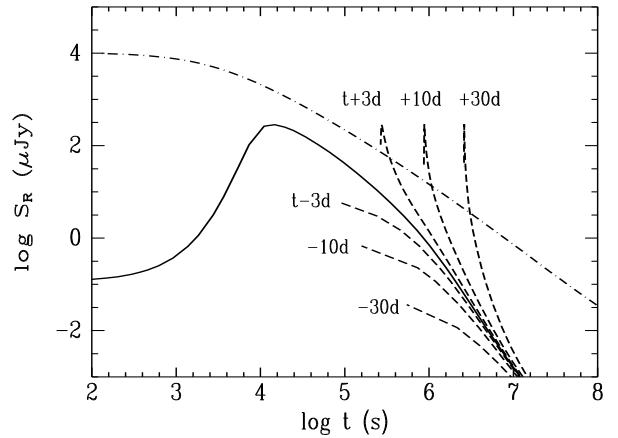


Figure 4. The same as in Fig. 3, but this time the light curve of the jetted GRB orphan is shifted.